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APPENDIX I  
SINGLE CELL THEORY

A STRUCTURAL MODEL FOR COMPOSITE  
ROTOR BLADES AND LIFTING SURFACES\*

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EXTENDED ABSTRACT

Introduction

Composite material systems are currently primary candidates for aerospace structures. One key reason for this is the design flexibility that they offer. It is possible to tailor the material and manufacturing approach to the application. Two notable examples are the wing of the Grumman/USAF/DARPA X-29 and rotor blades under development by the U.S.A. Aerostructures Directorate (AVSCOM), Langley Research Center.<sup>1</sup>

A working definition of elastic or structural tailoring is the use of structural concept, fiber orientation, ply stacking sequence and a blend of materials to achieve specific performance goals. In the design process, choices of materials and dimensions are made which produce specific response characteristics which permit the selected goals to be achieved. Common choices for tailoring goals are preventing instabilities or vibration resonances or enhancing damage tolerance.

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An essential, enabling factor in the design of tailored composite structures is structural modeling that accurately, but simply, characterizes response. Simplicity is needed as cause-effect relationships between configuration and response must be clearly understood and numerous design iterations are required. The objective of this paper is to improve the single closed-cell beam model previously developed by the senior author<sup>2</sup> for composite rotor blades or lifting surfaces and to demonstrate its usefulness in applications.

#### Modeling Improvements

Two major improvements have been made in the model of Reference 2. They are:

- (1) More accurate representation of twisting deformation; and
- (2) Simplification of the representation of torsion-related warping.

#### Outline of the Present Work

An analysis of the behavior of the model Langley rotor blade under three static load cases appears in Reference 1. The model rotor cross section is shown in Figure 1. The same three loading cases have been considered. The first case is bending due to lift and blade weight, the second is pure torque and the third is axial loading due to centrifugal force.

In Reference 1, a classical version of the theory of Reference 2 is compared with an extensive finite element simulation based upon orthotropic shell elements. Attention is focused upon the small discrepancies in the earlier study which are correctly

attributed to torsion-related warping. This confirms the findings reported in Reference 3. Also, an assessment of nonclassical effects in bending behavior has been made.

#### Bending Due to Lift and Blade Weight

Beam deflection results from the bending case appear in Figure 2. Bernouli-Euler, the classical engineering beam theory, results are denoted by "BE." This model is overly stiff. Also presented are three shear deformation models, SD1, SD2 and SD3, and the finite element results.

The shear deformation model S1 is an approximation obtained by setting the coupling stiffness  $C_{25}$  and  $C_{36}$  in Reference 2 to zero. This is the classical shear deformation model in the spirit of Timoshenko. Clearly it is overly stiff also. This direct transverse shear effect is small for a beam of this slenderness.

The complete theory, which includes all coupling effects, is denoted SD3. It provides good agreement with the finite element results.

The approximation denoted SD2 is obtained by neglecting completely the classical shear deformation effect accounted for in SD1 in favor of the coupling mechanism associated with  $C_{25}$  and  $C_{36}$ . This model, therefore, includes only deformations due to the transverse shear-bending coupling and the usual bending contribution. The magnitude of this new, unexplored form of elastic coupling is seen to be enormous by comparing SD2 and BE results. This is a finding of major importance in understanding the behavior.

The SD2 or SD3 models are required in this application in order to get sufficiently accurate predictions. This clearly excludes the earlier classical type theory of Mansfield and Sobey<sup>4</sup> from practical use.

#### Pure Torque

The classical St. Venant torsion theory result (without warping) is compared to the complete beam theory (CBT) and the finite element results in Figure 3. The CBT results, which differ from the classical (CL) only by the warping effect, are in excellent agreement with the finite element analysis. Restrained warping creates a boundary layer zone near the blade root that acts to stiffen the blade and reduce the angle of twist.

#### Axial Loading Due to Centrifugal Force

This case is of the utmost importance because extension-twist coupling is to be used to control blade stall, an application of elastic tailoring. The discrepancy between analytical predictions and the finite element analysis was the greatest for this case. Classical theory was too soft and it overestimated the twist angle, a condition that is not conservative in view of the stated purpose of the model demonstration.

As in the pure torsion case, the neglect of torsion-related warping is the reason for the discrepancy between coupled beam theory and the finite element analysis.

The twist angle distribution appears in Figure 4. The use of CBT brings the beam theory results in very good agreement with the finite element analysis. The rate of twist distribution is given in Figure 5. Again, the agreement is very good.

## Conclusions

In structures designed for extension-twist coupling, a high degree of bending-shear coupling is present which drastically causes the structure to be more flexible in bending. The impact of this effect on system performance must be assessed.

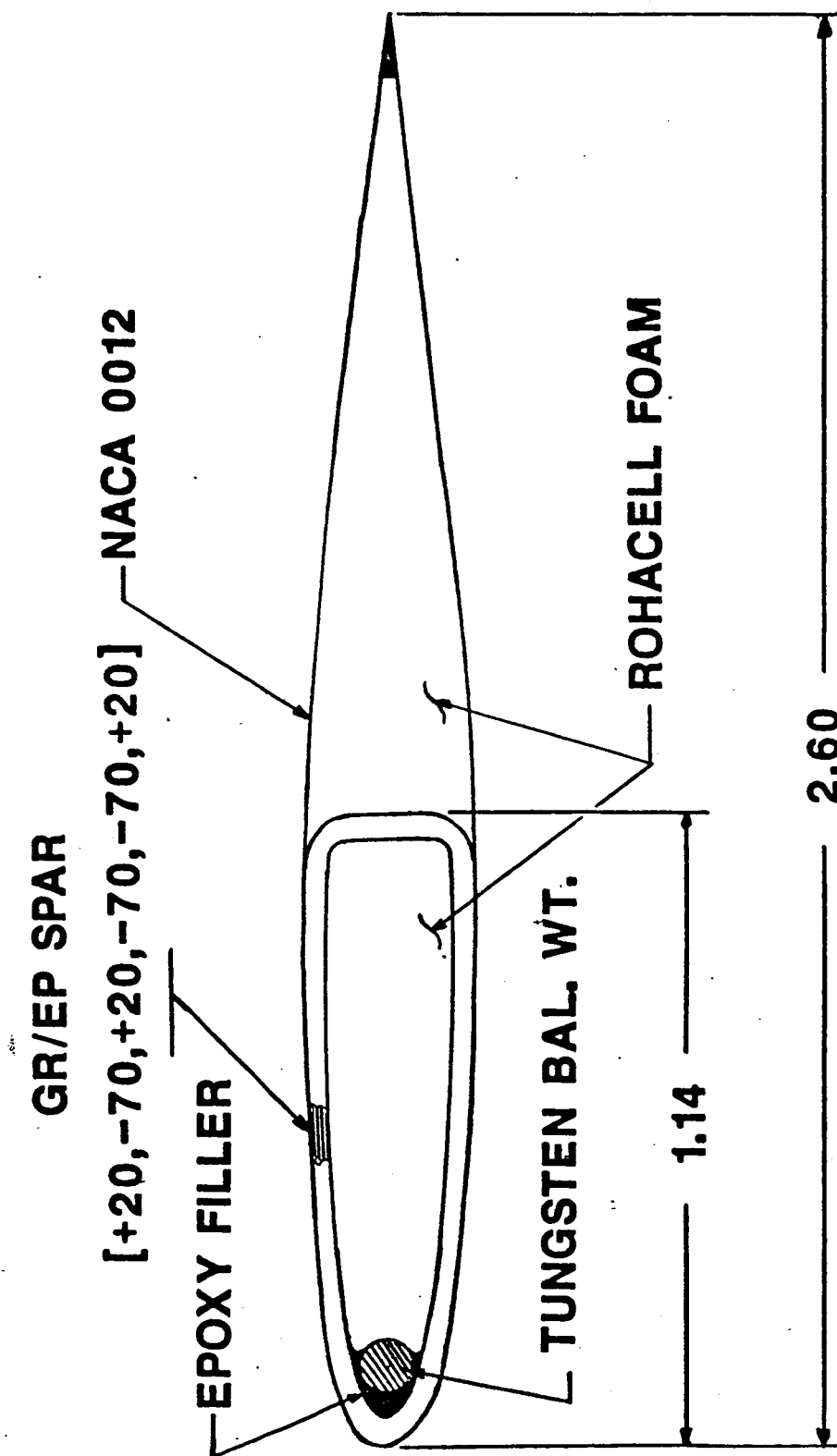
Torsion-related warping is significant enough to warrant its inclusion in the beam analysis. With warping accounted for, the coupled beam theory is extremely accurate and easy to use.

## References

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3. Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "Composite Box Beam Analysis: Theory and Experiments," to appear in the January 1987 issue of the Journal of Reinforced Plastics and Composites.
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FIG. 1

# MODEL ROTOR CROSS SECTION



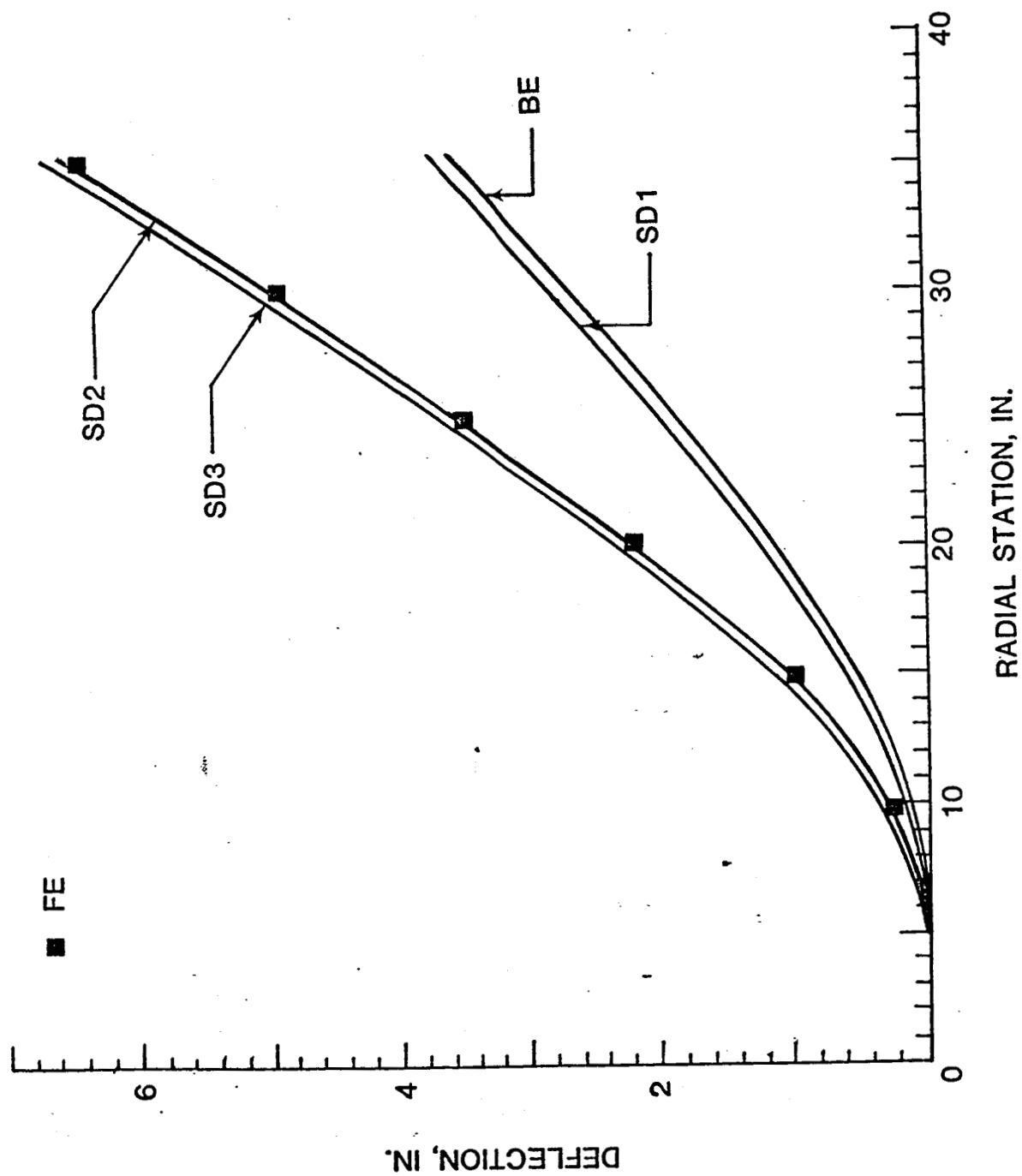
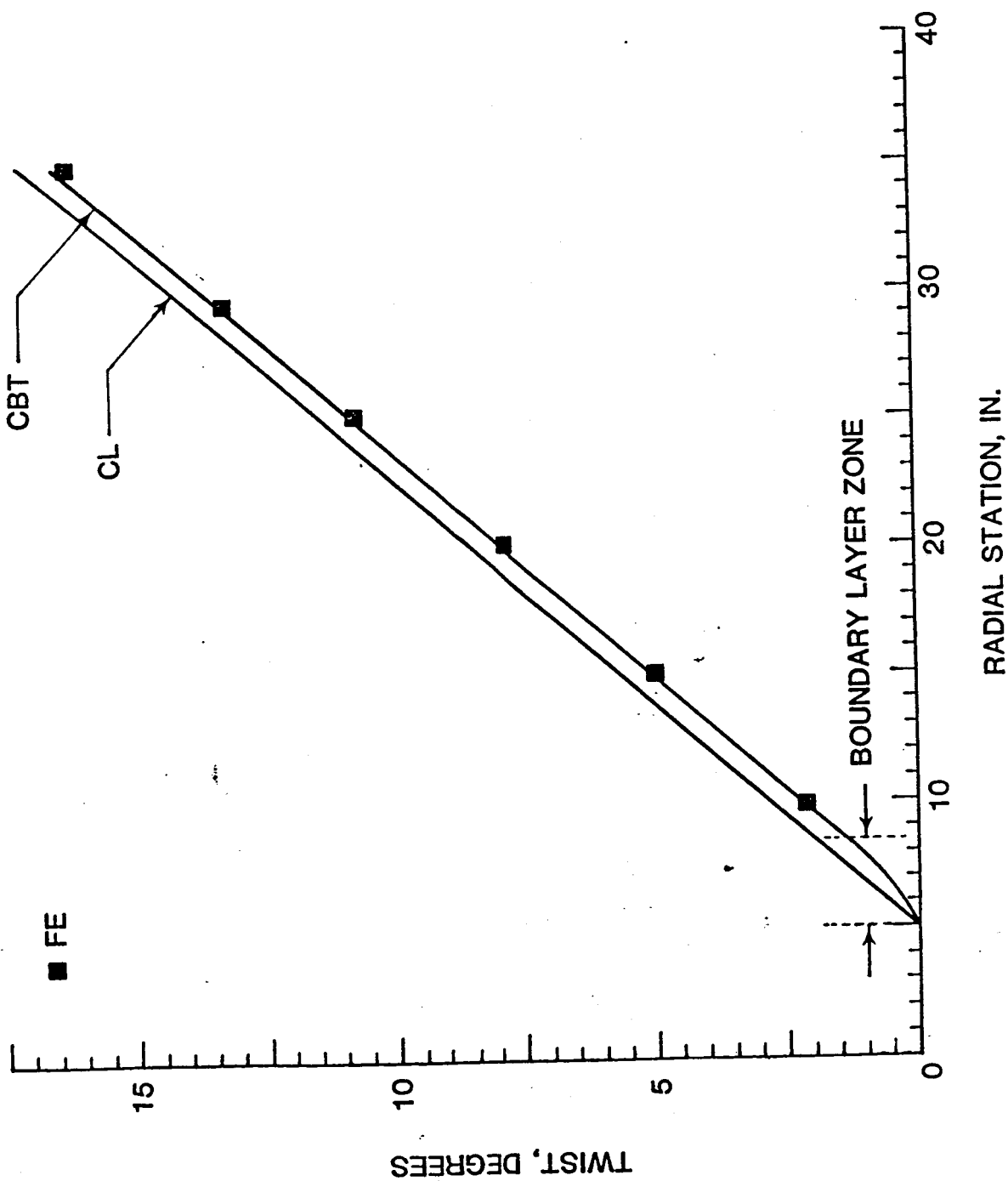


FIGURE 2  
BEAM DEFLECTION DUE TO  
LIFT AND BLADE WEIGHT





RADIAL STATION, IN.

FIGURE 3  
TWIST DUE TO APPLIED TORQUE

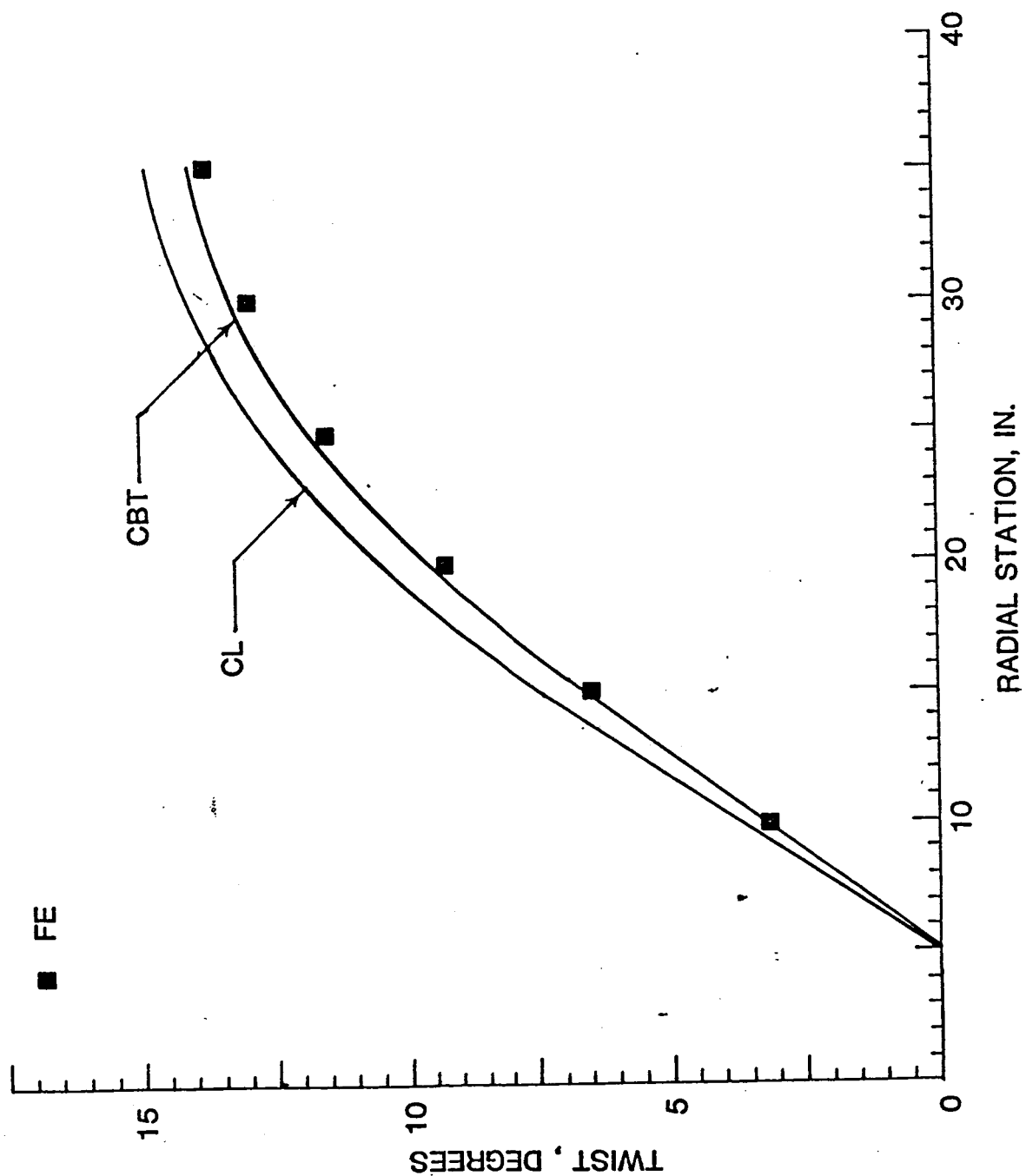


FIGURE 4  
TWIST DUE TO CENTRIFUGAL FORCE

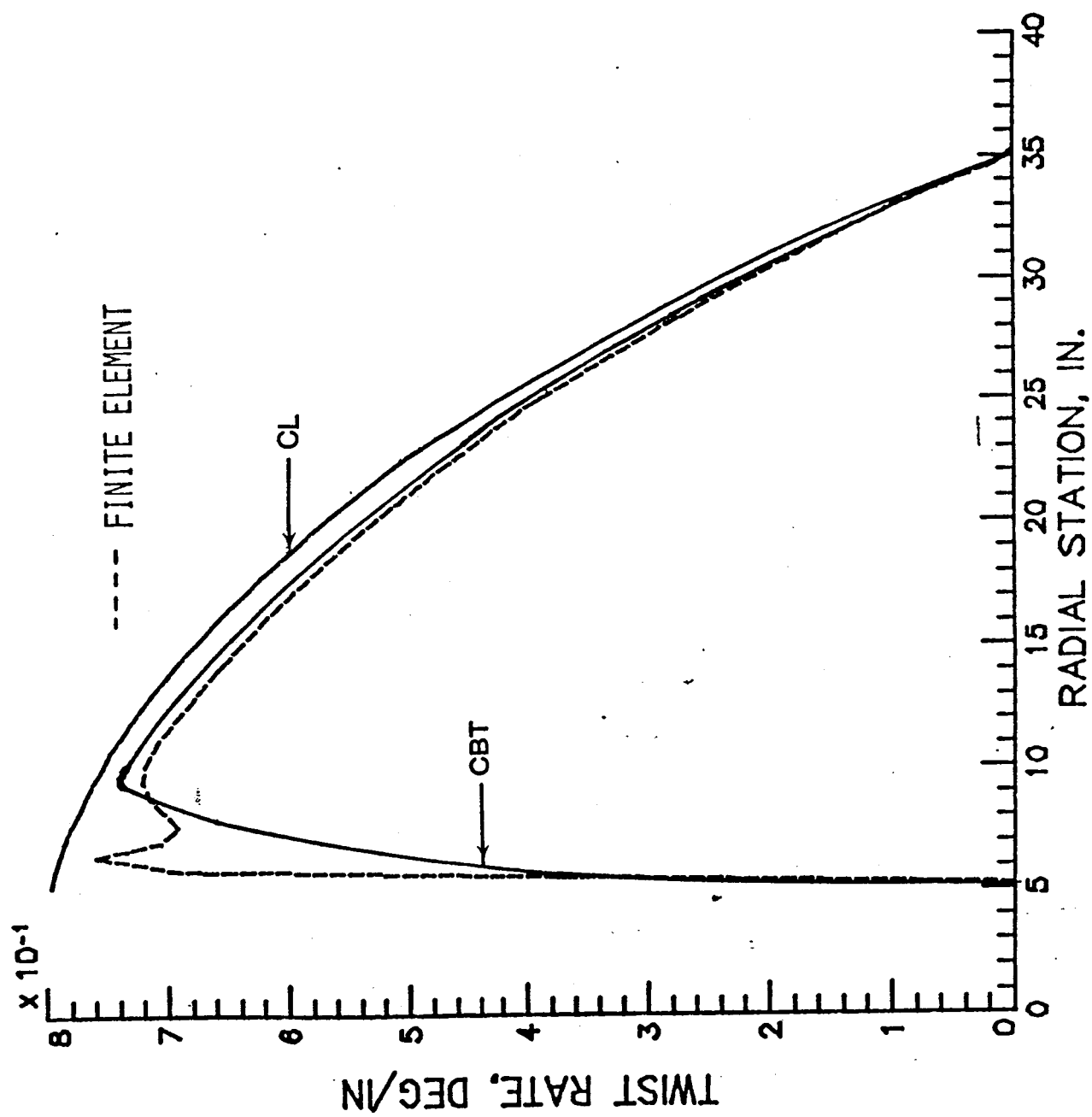


Figure 5. - Twist rate due to centrifugal force.